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Measuring Accuracy of Two 3D Printing Materials

Mudassir Ali

Bowling Green State University

MEASURING ACCURACY OF TWO 3D PRINTING MATERIALS

Mudassir Ali

Major Project

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Committee:

Dr. Sudershan Jetley (Chair)

Dr. Todd C Waggoner

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Chapter I: Introduction

Context of the Problem

There are variety of manufacturing technologies generally called Rapid Prototyping (RP). These technologies include Stereolithography, Selective Laser Sintering (SLS), Fused Deposition Manufacturing (FDM) and Three Dimensional Printing (3D Printing). These technologies are capable of directly generating physical objects from computer-aided design (CAD) files. A common feature in these technologies are that the part is produced by adding materials instead of removing materials as practiced in traditional manufacturing technologies. This simplifies the 3D part producing processes to 2D layer adding processes such that a part can be produced directly from its model. The machines using many of the RP technologies to build parts are often known as 3D printers.

3D printing is now revolutionized with the technology of additive manufacturing. Additive manufacturing (AM) is the formalized term for what used to be called rapid prototyping and is popularly called 3D Printing. The term rapid prototyping (RP) is used in a variety of industries to describe a process for rapidly creating a system or part before finalizing it. (Ian Gibson, 2010)

Part accuracy is one of the important aspect in the manufacturing industry. Though all the printing materials come with specifications, but the suppliers and manufactures does not specify the accuracy of the materials. They seldom talk about which material is more accurate when it comes to part accuracy. In this study we established a study which compares the accuracy of the materials in consideration and performed an experiment to establish the superiority of a material in terms of accuracy over each other. The overall inaccuracy of the parts being built by RP technology has been one of the major challenges that need to be overcome. Errors due to warpage and shrinking dominate the inaccuracy of the part. The thermoplastic ABS material used in FDM machines experiences a volume change when it is heated and then extruded onto a build platform. (B Fritz, 2001)

Our RP manufacturing Lab has several RP machines namely 3D sense, MakerBot replicator, XYZ Davinci, Flashforge Creator Pro, Solidoodle and an industrial scale Stratasys 768. These RP machines are used to give an insight of industrial application of Computer Aided Design and Computer Aided Manufacturing (CAD-CAM) to the students. The students design their part in CAD software mainly Solidworks, the part file or the object is later printed in one of the RP machines. The printed object is physically analyzed from the design, dimensional accuracy, durability and fineness point of view. One of the main challenges in the RP industry is the part accuracy that must be improved upon. It has been observed in the earlier research project that parts being printed/manufactured tend to warp and shrink from their intended original dimensions. Many factors are to be blamed for the in warping and shrinkage which will be discussed following sections.

Earlier the materials used to manufacture had low yield strength. With the advancement in material science, the photopolymers and thermoplastics used now have much higher yield strength and durability. The strength of RP materials is sufficient for small scale applications, but does not always satisfy the strength and accuracy requirements for large scale applications for industrial purposes such as printing car spare parts. The use of stronger materials with more accuracy and strength will enable RP to produce parts to satisfy the requirements of heavy industrial applications.

The Department of Engineering Technologies in Bowling Green State University have recently added a research RP machine Flashforge Creator in its 3D printers. It is desirable to evaluate the accuracy of the materials we will be using for the printing. The department is likely use two different materials namely ABS and PLA. The machine’s general specifications for accuracy is provided by the manufacturer and is discussed in the section II. However since we are using different materials it’s desirable to analyze the accuracy of the said materials for their optimal utilization and it should help the students to design their parts considering the accuracy as one of the factors.

Statement of the Problem

The purpose of this project was to compare the dimensional accuracy of 3D printed parts of Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS) when compared with dimensions of the CAD models from which these parts are printed. The parts were printed using the Rapid Prototyping machine Creator Pro Dual Extension built by Flashforge. The parts consisted of small rectangular prisms and spheres.

Objectives of the study

In order to conduct this project following objectives will be achieved.

1. Design the Sphere and a rectangular prism in CAD_CAM software Solidworks.
2. Print models in Creator, ten each of PLA and ABS.
3. Print models in two different sets of dimensions.
4. Measure the dimension of the printed models using micrometers.
5. Compare them against the ideal dimension given in CAD model drawing and also compare them against each other.

Significance of the Study

The goal is to evaluate the limitations of the printing material, to rule out factors that do not contribute significantly to print accuracy, and to provide a practical, quantitative guide for accuracy measurement as an engineering tool. A methodology or a practical approach for calculating accuracy of a material will be developed which can be used in future to test accuracy. It will establish which material is more accurate and what is the reason behind it. Future students will get a guideline of conducting a research in RP FDM technology and will overcome the limitations this study has.

Assumptions/Limitations

1. The research is limited to the use of ABS and PLA, since they are the most common materials used for 3D printing and due to availability restrictions.
2. The RP machine Flashforge Creator Pro will be used because this is the new machine of interest to the Department and is one of the industrial scale RP machine.
3. Due to budgetary limitations only ten parts of each type will be printed.

Definitions of Terms

3D Printing

It is a process of making a prototype from a three-dimensional digital model by laying down several consecutive thin layers of a material.

Additive Manufacturing

Additive manufacturing is the process of building object by adding layer upon layer of the material. (LaMonica, 2013)

STL Files

STL (StereoLithography) is a file format native to the stereolithography CAD software created by 3D Systems. STL file format is a polyhedral representation of a surface model with triangular facets which facets must obey the vertex to vertex rule and facet orientation rule. The first commercial rapid prototyping technology was developed by Charles "Chuck" Hull. (M. Vatani, 2009).

PLA

Polylactic Acid is a thermoplastic and one of the most dominant plastic in 3D printing industry. It is a biodegradable polymer. (Chilson, 2013)

ABS

Acrylonitrile butadiene styrene (ABS) is a thermoplastic and dominant printing material in the 3D printing industry. (Chilson, 2013)

Plastic Filament

It is the print material which is wound over the coil and supplies the material to the extruder while printing the job.

Fused deposition modeling

This technology builds layer-by-layer from the bottom up by heating and extruding thermoplastic filament. (Sratasys, 1990)

Rafts or Support Material

It provides the support base or the contact surface so that the model being printed sticks to the print bed and the print material does not start warping upwards.

Chapter II: Review of Literature

Introduction to 3D Printing

On February 12, 2013, President Obama gave his State of the Union address from the America Makes - National Additive Manufacturing Innovation Institute (NAMII) in Youngstown, Ohio and said "A once-shuttered warehouse is now a state-of-the art lab where new workers are mastering the 3-D printing that has the potential to revolutionize the way we make almost everything." (Stephanie M. Santoso, 2013)

It was in 1984 that Charles Hull, co-founder of 3D systems invented stereolithography, a printing process that enables a tangible 3D object to be created from digital data. (Xue Yan, 1996) The basic principle of Additive Manufacturing (AM) technology is that a model, initially generated using a three-dimensional Computer-Aided Design (3D CAD) system, can be fabricated directly without the need for process planning.

The key to how AM works is that parts are made by adding material in layers, each layer is a thin cross-section of the part derived from the original CAD data. Obviously in the physical world, each layer must have a finite thickness to it and so the resulting part will be an approximation of the original data. The thinner each layer is, the closer the final part will be to the original. All commercialized AM machines use a layer-based approach, they differ mainly in the materials that can be used, how the layers are created, and how the layers are bonded to each other. Such differences determine factors like the accuracy of the final part plus its material properties and mechanical properties. They also determine factors like the time taken for the part to be printed, how much post-processing is required, the size of the AM machine used, amount of material used and the overall expenses of the machine and process. (Ian Gibson, 2010)

AM technology has developed over time as materials, accuracy, and the overall quality of the output improved. Models were quickly employed to supply information about what is known as the “3 Fs” of Form, Fit, and Function. The initial models were used to help fully appreciate the shape and general purpose of a design (Form). Improved accuracy in the process meant that components were capable of being built to the tolerances required for assembly purposes (Fit). Improved material properties meant that parts could be properly handled so that they could be assessed according to how they would eventually work (Function). (Ian Gibson, 2010)

AM is now frequently referred to as one of a series of disruptive technologies that are changing the way we design products and set up new businesses.

In figure 1 a block diagram of a common procedure of 3D printing is depicted:

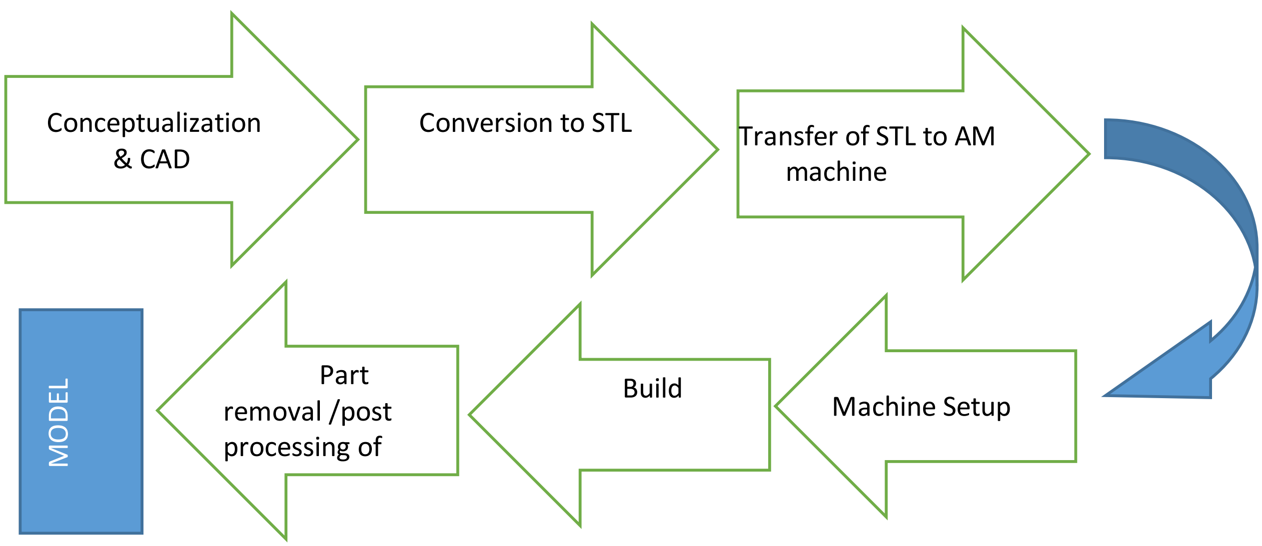

Figure 1: Block Diagram of 3D Printing process

Significance of Layers

A key principle of AM part manufacturing is the implementation of the layers as limited 2D cross-sections of the 3D model. As mentioned above every AM technology builds parts using layers of material added together, and certainly all commercial systems work on this principle, probably due to the simplification of building 3D objects. Using 2D representations to represent cross-sections of a more complex 3D feature has been common in many applications outside AM. For cartographers use a line of constant height to represent hills and other geographical reliefs. These contour lines, can be used as plates that can be stacked to form representations of geographical regions. The gaps between these 2D cross-sections cannot be precisely represented and are therefore approximated, or interpolated, in the form of continuity curves connecting these layers. Such techniques can also be used to provide a 3D representation of other physical properties, like isobars or isotherms on weather maps. Layered approach is one of the basic component which defines the accuracy of the part. Layer by layer printing is depicted in the figure 2. (Ian Gibson, 2010)

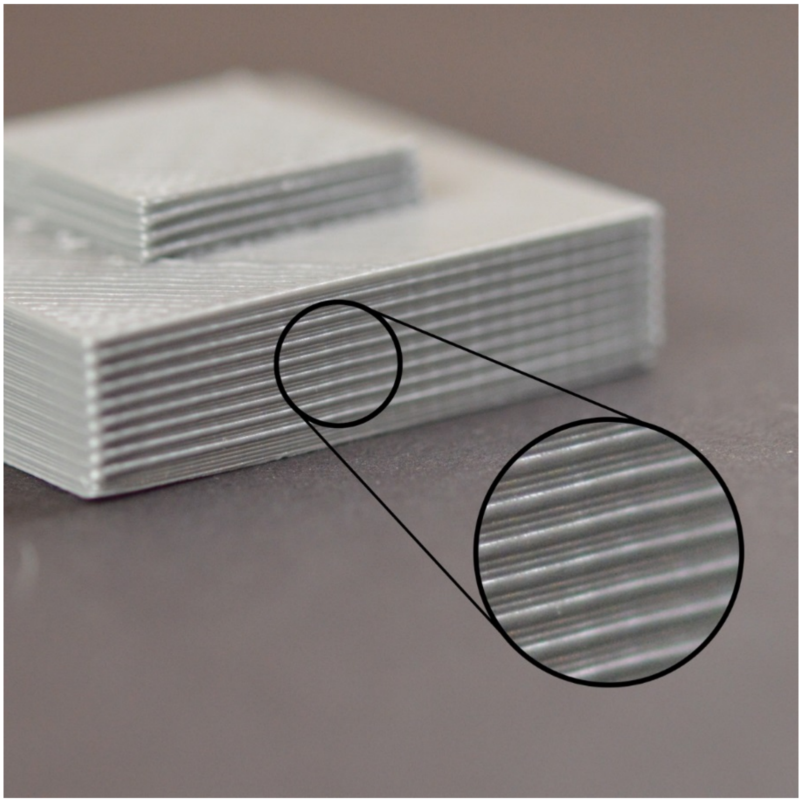

Figure 2: Layer by Layer printing (Courtesy: simplify3d.com)

Fused Deposition Modelling (FDM)

FDM is the most common extrusion based additive manufacturing technology, produced and developed by Stratasys. FDM uses a heating chamber where the raw material is fed and it gets liquefied. It is commonly known as extruder where the material is fed in and a liquefied thermoplastic is extruded on the print bed. Parts made using FDM are among the strongest for any polymer-based additive manufacturing process. (Heller, 2015)

The most common materials used for FDM are Acrylonitrile butadiene styrene (ABS) and Polylactide (PLA), with their characteristics of becoming a liquid substance with predictable flow properties in response to heat, while forming a reliable solid once cooled. This process of heating and cooling plastic, is prone to random variation, with undesirable results depending on the size of the object being modeled. Differences in material properties across manufacturers and even among different material from the same manufacturer can result in very different printing results. (Hernandez, 2015)

In FDM technology accuracy which is ability to meet precise physical dimensions, consistent shapes, and predictable surface finish is important in the case of engineered mechanical devices. 3D printing, being an additive manufacturing technology in nature, provides an opportunity to create unique components that was not possible in the traditional subtractive technologies to replicate the part.

Selective Laser Sintering

Selective laser Sintering is a layer manufacturing process which allows user to generate complex 3D structures by consolidating successive layers of powder material on top of each other. Consolidation is obtained by processing the selected areas using the thermal energy supplied by a focused laser beam. (J P Kruth, 2004)

STL File

Stereo lithography file format is widely used as standard in the rapid prototyping industry. Layer-by-layer fabrication method plays an important role in improving the accuracy of the manufacturing. There are many existing interfaces for graphics exchange such as initial graphics exchange Specification (IGES), standard for the exchange of product model data (STEP), computerized tomography (CT), Layer exchange ASCII Format (LEAF) etc.

STL file format because of its simple topology and powerful nature in tessellation of almost all surfaces is widely accepted and supported by most commercial Computer Aided Geometric Design (CAGD) software and layer fabrication equipment. STL file format is made up of only one type of element, a triangular facet, which is defined by its normal and three vertices. All the triangular facets described in a STL format file constitute a triangular mesh to approximate Modeling surfaces. In other words STL file format is a polyhedral representation of a surface model with triangular facets. STL is reasonably suitable to be the interface between object modeling and layer-by layer fabrication. (M. Vatani, 2009)

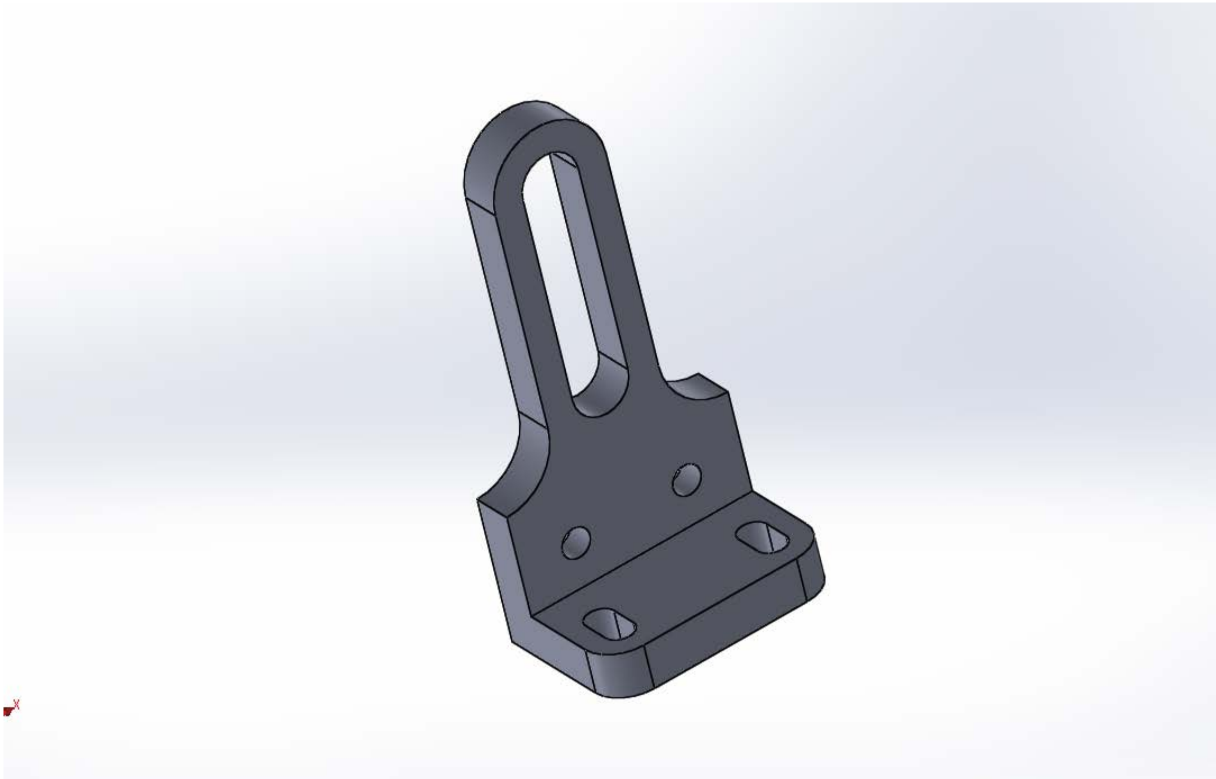

Figure 3: Solid Model of Bracket designed in our CAD lab.

Figure 3 shows the solid model of a bracket designed in Solidworks. Figure 4 depicts the STL file of the bracket, we can observe the polyhedral representation of a surface with triangular facets. Mesh is generated on each facets to model the surfaces

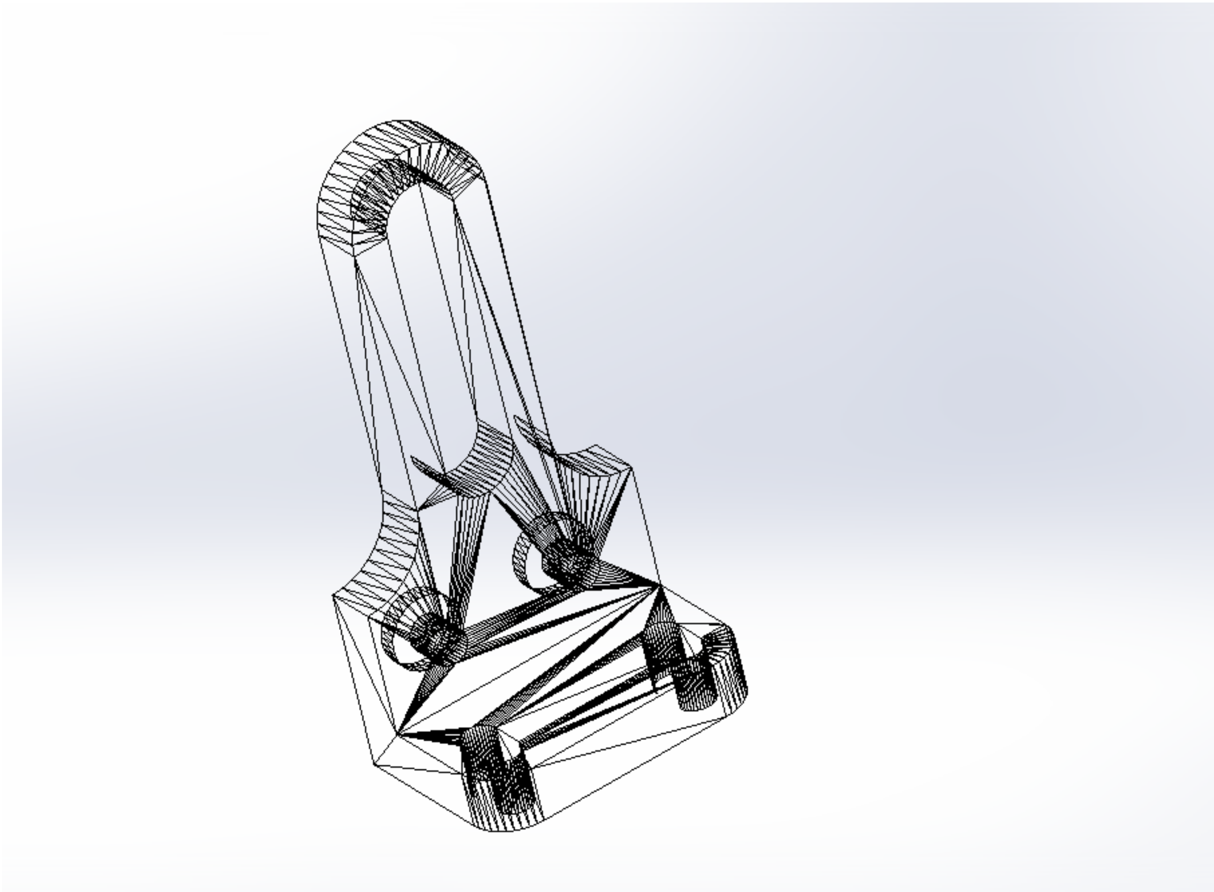

Figure 4: Depiction of STL file of Bracket

Factors Affecting Accuracy

As already mentioned the most common materials used for FDM are ABS and PLA, with their property of becoming a liquid substance when heated, while forming a reliable solid once cooled. This process of heating and cooling plastic, is still prone to random variation, with unpredictable results depending on the shape and size of the object being printed. Differences in material properties across manufacturers and even across different material lots from the same manufacturer can result in very different printing results. It requires user intervention to modify few printer parameters until required prints are achieved. (Hernandez, 2015)

There are a number of factors, which affect achievable accuracy in different manner. At first there are the basic process parameters such as the scaling factor and the saturation value. Those factors are recommended by the system manufacturer with different values for different materials and purposes and should be checked for every new build. Some other factors have much higher impact on the accuracy and these are: (Beer, 2006)

- Material used
- Nominal dimensions, small, medium, large.
- Build orientation.
- Geometric features and their topology e.g. open or Closed contours.
- Wall thickness shell, rafts, solid.
- Post treatment procedures.
- Infiltrating agent.

Raw Materials

Plastics engineers divide plastics into two main classifications: thermoplastics and thermosetting plastics. Thermoplastics melt when heated and do not change their internal composition when heated, and they can be melted and re-melted several times. Thermosetting polymers solidify when heated and they are only used once, because their internal composition modifies when heated, thermosetting polymers cannot be melted back down into a reusable liquid form.

Most consumer printers use a type of thermoplastic called ABS, the same kind used in LEGO bricks. STL based 3D printers use light-sensitive thermosetting polymers. Printers that use laser sintering use powdered thermoplastic. (Hod Lipson, 2013)

3D printers can also work with another category of plastics, soft plastics, known as elastomers. These rubber like materials have various elastic properties. Some of these materials, like silicone, can be squeezed through a syringe and then air-dried. Other soft, rubbery objects can be printed by melting a thermoplastic elastomer, similar to the process used to fabricate hard plastic. (Hod Lipson, 2013)

Glass, one of the most common materials used by humans, has been one of the slowest materials to gain popularity in 3D printing. Glass being hydrophobic, results in not adhering well. Powdered glass is unpredictable when exposed to heat. Researchers in University of Washington have successfully printed objects made of recycled glass in the research lab (Grant Marchelli, 2011). Commercial application of glass printing is still mostly for art and jewelry. (Hod Lipson, 2013)

Thermoplastics

There are dozens of kinds of thermoplastics, with varying degree of in crystallinity and density. Some types that are commonly produced today are polyurethane, polypropylene, polycarbonate, and acrylic. Celluloid which is considered the first thermoplastic, made its appearance in the mid-1800s and reigned in the industry for approximately 100 years. The most common 3D printing material used nowadays are PLA and ABS. These are further discussed in the following sections. (Maier, 2016)

ABS

ABS as a polymer can take numerous forms and can be modified to have multiple properties. It is a strong plastic with some flexibility. It has excellent impact strength at low temperatures.

Natural ABS before being processed is a soft milky beige in color. The flexibility of ABS makes it favorable in creating interlocking components or connected pieces. ABS is soluble in Acetone, which allows welding of parts together with a few drops, and create high gloss by brushing or dipping full pieces in Acetone. Its strength, flexibility, machinability, and higher temperature resistance makes it most preferred plastic in the 3D industry. (Chilson, 2013). The specific properties of ABS are shown in Table 1.

ABS softens at a higher temperature than PLA, which makes parts printed in ABS more resistant to warping under higher temperatures. It tends to warp and peel, and often will not stick well to an unheated, or under-heated print-bed.

While printing the single greatest hurdle in ABS is tendency of curling upwards from the surface in direct contact with the 3D Printer's print bed. Various solutions can be used to overcome this problem such as applying Acetone on the print bed prior to printing.

Generally, it is easier for manufacturers to attain better tolerances with ABS than with PLA. However, the extrusion characteristics of PLA allow for finer feature detail on a well-tuned machine.

Table 1: ABS Properties (Chilson, 2013)

ABS Properties
Extrude at 225℃
Requires heated bed
Works reasonably well without cooling
Adheres best to polyimide tape
Filament tolerances are usually tighter
Prone to cracking, delamination, and warping
Flexible with Flexular strength of 11,000psi
Can be bonded using adhesives or solvents (Acetone or MEK)
Petroleum Based
High toughness with tensile strength of 6,500psi
Impact Resistance
Resistant to Aqueous Acids
Heat Resistant to 105 C
Density is 1.03 to 1.38g/cm^3

PLA

PLA is a bio material produced from crops such as corn, potatoes or sugar-beets. Hence, PLA is considered a more eco-friendly plastic compared to ABS which is petroleum based. It is strong, and more rigid when compared to ABS, and sometimes it is difficult to work with in complicated interlocking assemblies and pin-joints. PLA printed objects normally have a glossier look and feel compared to the objects printed in ABS. With a little more effort, PLA can also be sanded and machined. One of the drawback is its lower melting temperature which makes it unsuitable for many applications. For example if a PLA part is left in a closed car for a day in the sun the object can droop and deform. PLA is used primarily in food packaging and containers. It is naturally transparent and can be colored to various degrees of translucency and opacity. (Chilson, 2013)

Accuracy of parts is much less in PLA when compared to ABS. PLA undergoes a phase-change when heated and becomes much more liquid. If actively cooled, much sharper details can be seen on printed corners without the risk of cracking or warping. The increased flow can also lead to stronger binding between layers, improving the strength of the printed part. If compared to PLA, it is easy to recycle ABS. Some general properties of PLA are given in Table 2.

Table 2: PLA Properties (Chilson, 2013)

PLA Properties
Extrude at 180-200°C
Benefits from heated bed
Benefits greatly from cooling while printing
Adheres well to printbed
Prone to curling of corners and overhangs
Flexular Strength of 8,020 psi
Tensile Strength of 8.383 psi
Plant Based
Can be bonded using Adhesive

Support Material

Support Material is an important factor in 3D printing. As the part is printed layer by layer what will prevent material from falling to the ground especially in the undercuts and parts with hollow features. Cue support material or support structures are the rigid pieces of base material erected in a lattice next to the object being printed. After the part is printed, support material is removed by aggressive sanding or clipping it away with scrapper. It is a time consuming process and can cause dimensional inaccuracies. Moreover, many parts have features that simply cannot be accessed by hand or machine. In these particular cases, support structures will remain in those areas as removing them can cause deformation. Technologies like FDM and have introduced a support material that dissolves when placed in a bath of chemicals. Direct Metal Laser Sintering (DMLS) and Selective Laser Sintering (SLS) use the surrounding powder itself to support the printed part. (Armbruster, 2012)

Recent Development and Forecast

In today's manufacturing industry be it large scale or at Nano scale 3D printing or Additive Manufacturing has founded its place. In a recent Price water Cooper survey of more than hundred industrial manufacturers, two-thirds were already using 3-D printing. (Alan Earls, 2014)

As mentioned above 3D printing is being implemented and experimented in every possible field. From medical to electrical, it is being experimented wherever simple manufacturing is involved. For example Nano Dimension founded in 2012 develops advanced 3D printed electronics and a printer for multilayer Printed Circuit Boards (PCBs). PCBs is an integral part of our daily life. PCBs are used everywhere from microwaves to heating system displays and from smartphones to our car keys. (Dimension, 2015)

In a recently held National Plastic Expo in March 2015 at Orlando Florida where 3D printed cars were displayed. An extreme 3D printed model was of Shelby Cobra where Techmer a Polymer Suppliers who supplied the carbon fiber compounds to print the car where they used large scale STL. (Techmer, 2015)

The key materials science challenge is to create materials often called inks that can be the basis for printing different types of products, be it sensors, electronics or iron nails. For example, Xerox PARC is developing inks so circuits, antennas, and RFID (radio frequency identification) tags can be printed and applied directly to a product. (Ready S E, 2013)

The renowned name in the 3D printing industry Stratasys showcased the Dental Selection 3D printer in recently held International Dental Show in March 2015 in Cologne, Germany. The triple-jetting technology was best used for the purpose of orthodontic labs. The printer is named as Object260. (Ollig, 2015)

Canalys, a market research firm, forecast changes ahead and predicts the worldwide business sector for 3D printers and its related services will develop from $2.5 billion in 2013 to $16.2 billion in 2018, an annual growth rate of 45.7 percent. (Alto, 2014)

Equipment and Print Materials

The printer used in this study is Creator Pro made by Flashforge, as shown in Figure 5. It is capable of printing objects with build volume of 9 x 6 x 6 inches, using a layer resolution of as high as 0.007 inches (0.17mm). It uses thermoplastic ABS but for our study we will be using ABS and PLA. The CAD/CAM software used is Solidworks 2016 release in designing the objects. The Solidworks interface allows user to make a STL file of the object providing a preview of sliced version of the part file.

Flashforge Creator Pro	
Maximum Part size	9*6*6 inches
Layer Thickness	0.1-0.3mm
Build Volume	5 Liters
Material	ABS/PLA
Software	ReplicatorG
Filament Diameter	1.75 mm
Nozzle Diameter	0.4 mm

Figure 5 Flashfroge Creator Pro

Conclusion

As an emerging technology it is important to understand the significance of the accuracy of the Rapid Manufacturing techniques which apart from manufacturing industry has many applications in medicine and dentistry. Important applications such as fit and function or pattern making for a number of molding and forming processes, the question of accuracy is of prime importance. Although all 3D printers have a general specified accuracy, the accuracy can vary due to many factors such as the properties of the print material. The material properties of ABS and PLA are quite different therefore it is important to see their effect on the printed parts.

Chapter III: Procedures

Restatement of the problem

The purpose of this project was to compare the dimensional accuracy of 3D printed parts of Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS) when compared with dimensions of the CAD models from which these parts are printed. The parts were printed using the Rapid Prototyping machine Creator Pro Dual Extension built by Flashforge. The parts consisted of small rectangular prisms and spheres.

Re statement of Objectives of the study

In order to conduct this project following objectives will be achieved.

1. Design the Sphere and a rectangular prism in CAD -CAM software Solidworks.
2. Print models in Creator, ten each of PLA and ABS.
3. Print models in three different dimensions.
4. Measure the dimension of the printed models using micrometers.
5. Compare the dimensions of parts printed with ABS to that of PLA printed parts.

Research Design Methodology

We designed the solid model in Solidworks 2015-2016. Solidworks is Computer Aided Design software based on Microsoft windows. The software has many built in features like Automatic interference and collision detection which makes sure all parts fit together before printing a physical prototype. (Solidworks, 2015) The CAD models designed for the research consisted of Rectangular prisms and spheres.

It has been observed from the previous experience that slight sagging and bending occurs at the bottom edges of the rectangular prisms. Therefore we measured the height away from the edges of the rectangular prism. Rectangular prism length and width corresponding to the diagram shown in Figure 6, was measured about half way along the height. The CAD drawing of rectangular prism type 1 is shown in Figure 7.

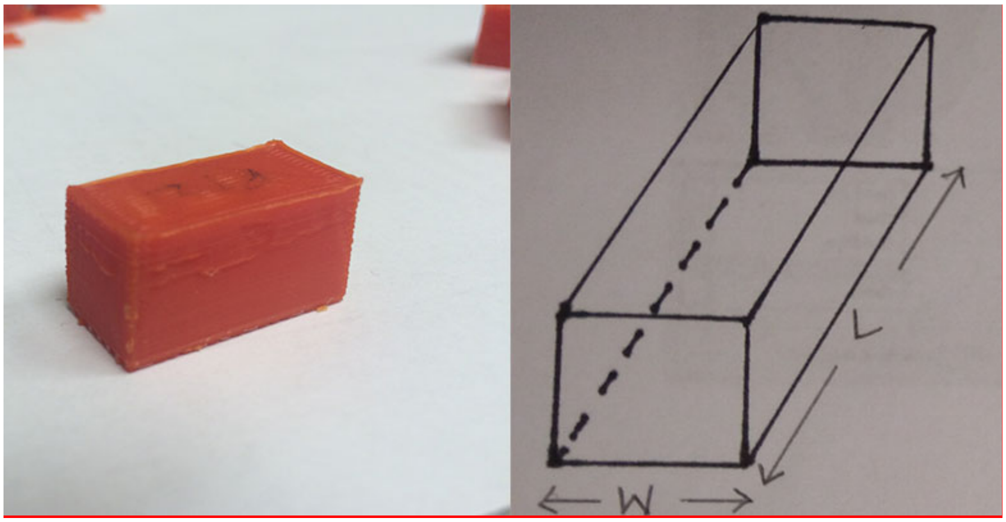

Figure 6: Rectangular Prism and its measurement notations.

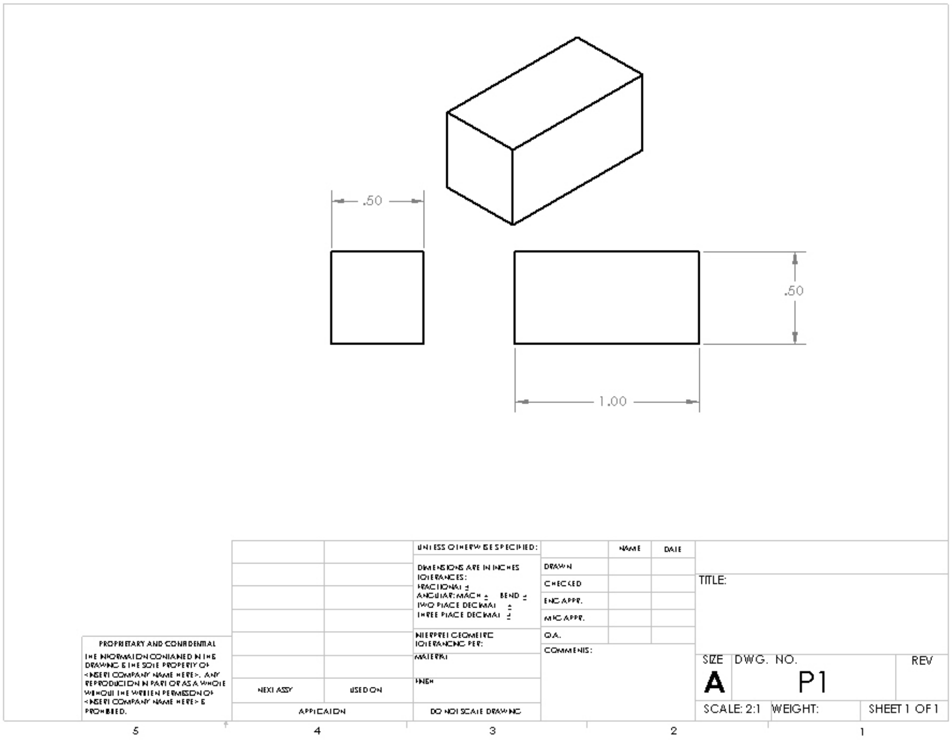

Figure 7: CAD drawing of rectangular prism type 1.

The spheres require supporting material during printing. This causes the bottom point of the sphere to become roughened and so measurements cannot be taken from this point. Therefore the measurement were taken from different points away from the base. Diameter was measure from thee different points as shown in Figure 8. The CAD drawing of sphere type 1 is shown in Figure 9.

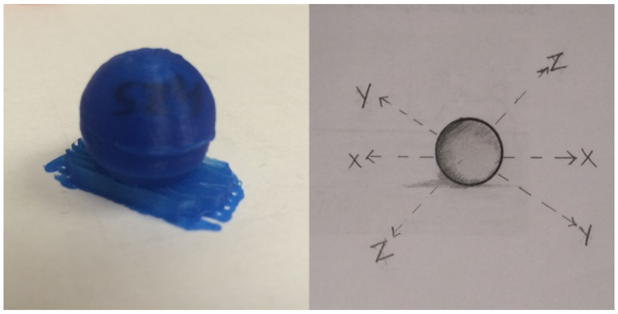

Figure 8: Sphere and its measurement notations.

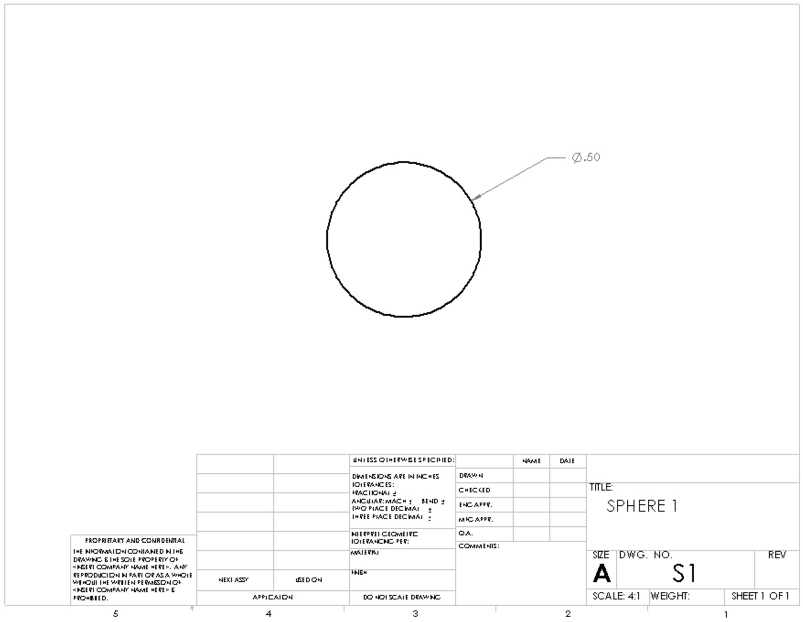

Figure 9: CAD drawing of sphere type 1.

As stated in the statement of the problem ten parts of each rectangular prism and spheres with each material were printed in Flashforge Creator pro using the standard manufacturer recommended parameters. The number of parts i.e. ten is chosen so as to satisfy the statistical requirement of the data analysis and for economic reason. Larger the data set more accurate will be the data analysis and more effective results can be achieved but this increases cost and time of printing which we needed to minimize due to availability of resources.

We printed multiple parts simultaneously to ease of print and to save print time. For multiple parts in single file we use the software slicer and imported STL file to Replicator G the software for the printer flashforge. The dimensions, in inches of the rectangular prisms and the spheres which were printed are tabulated in table 3.

In this research the 40 parts of ABS was printed. Two filament of different colors were used in printing ABS models. 20 parts with 10 each of rectangular prism and sphere were printed in white color and in blue color respectively. It was assumed that this would not cause any significant difference in the accuracy of the parts printed.

Table 3: Dimensions of the parts.

Part Type	Length	Width	Height	Diameter
Rectangular Prism type 1	1	0.5	0.5	--
Rectangular Prism type 2	0.75	0.5	0.5	--
Sphere type 1	--	--	--	0.5
Sphere type 2	--	--	--	0.75

These dimension are selected so that the parts easily fit the work envelope of the machine and to save the build material. The length and width of the printed rectangular prisms and the diameters of the printed spheres were measured using a 1 inch caliper micrometer which can measure to the accuracy of 0.0001 inches.

The sizes, materials and the number of parts printed are summarized in Table 3 and Table 4. As can be seen from table 4 a total of 80 parts were printed. The 3D drawings of the rectangular prisms and sphere modeled in Solidworks and their depicted STL files which were printed in the creator pro are shown in Figure 6 & 8 and Figure 7 & 9 respectively.

Table 4: Number of Parts printed.

Part Type	Number of Parts Printed		Total
	ABS	PLA	
Prism Type 1	10	10	20
Prism Type 2	10	10	20
Sphere Type 1	10	10	20
Sphere Type 2	10	10	20
			80

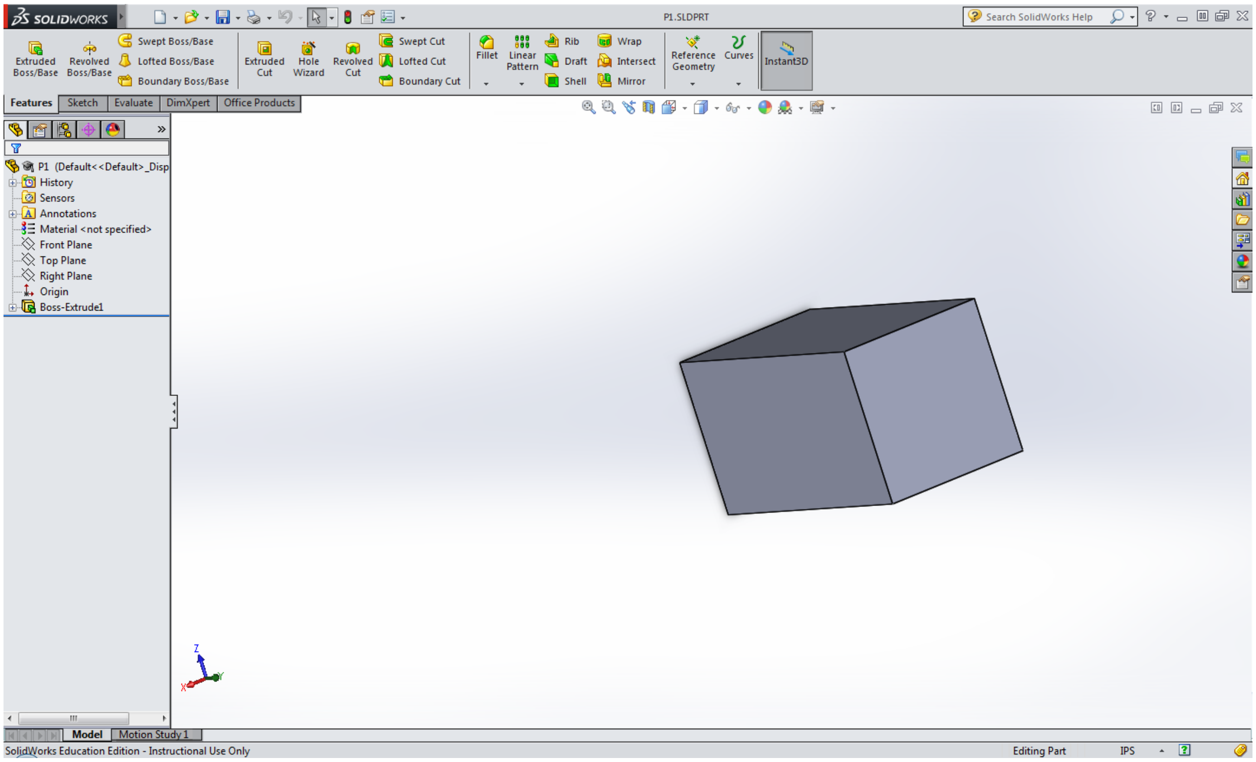

Figure 10: 3D CAD Model of Rectangular Prism 1

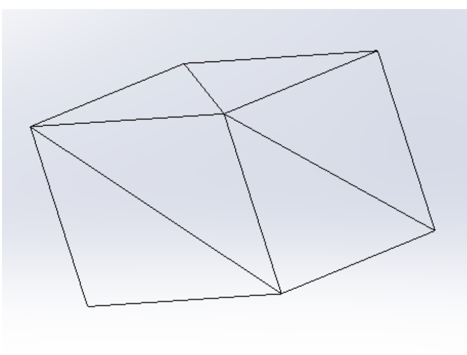

Figure 11: Depiction of STL file of the rectangular prism.

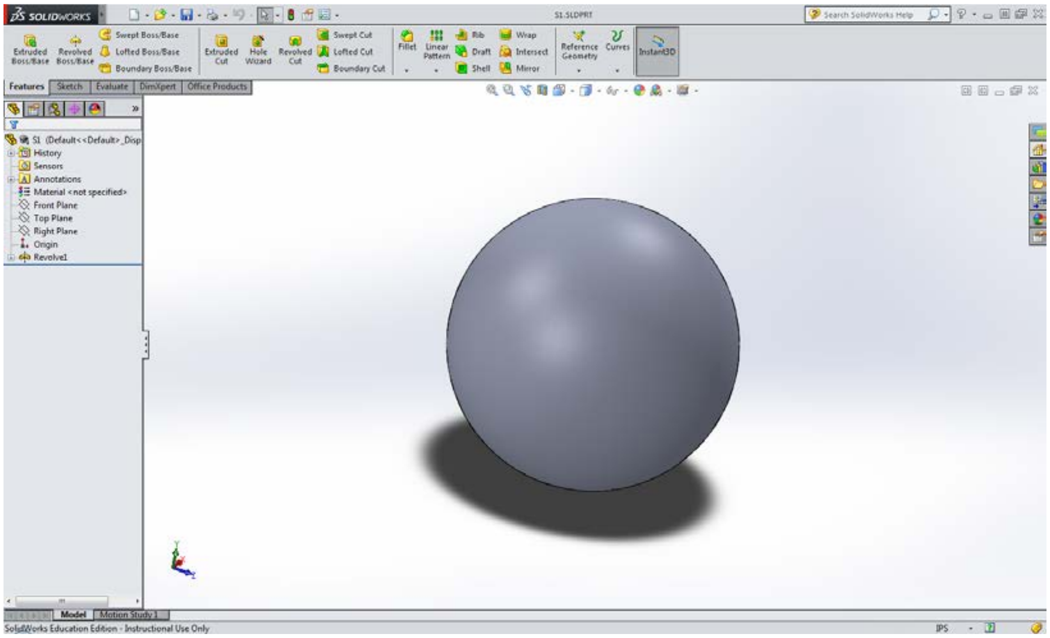

Figure 12: 3D model for sphere.

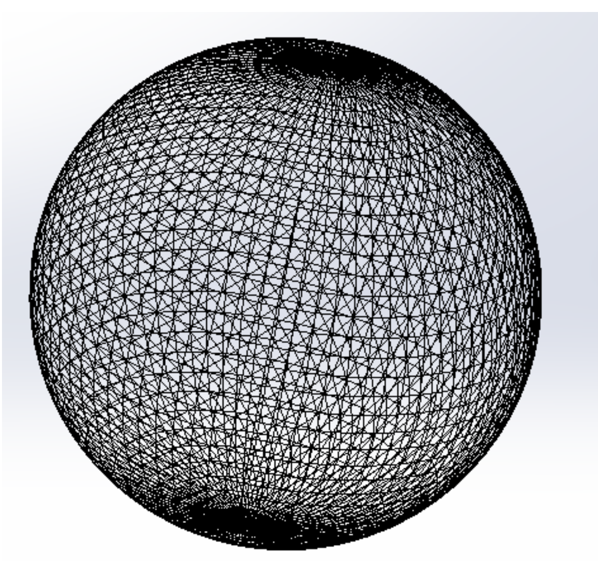

Figure 13: Depiction of STL file for sphere.

By measuring the length and width of each part of rectangular prism type 1 we get 40 readings as tabulated in Appendix A Table 5. Similar measurement was taken for the rectangular prism type 2 which can be viewed in Appendix A Table 7. Making the total readings of 80 measurements.

In case of sphere, as stated above, the diameter was measured at three different points as shown in Figure 7 so the total of 60 readings were recorded for each type of sphere. The diameters (D1, D2 and D3) measured for sphere types 1 are shown in the Appendix A Table 9. Similar measurement was taken for the sphere 2 which can be viewed in Appendix A Table 11 making the total readings of 120 measurements.

Data Analysis

F and t-tests

Mean and standard deviation of the length, width and the diameter were calculated from the data. Following analysis were followed:

Let us define a variable $Ig(x) = |L - x|$ as the magnitude of inaccuracy.

Where L is the ideal i.e. designed length of rectangular prism and x is the measured length of the prism. The value of L and W will change with the part in consideration, as per Table 3. In case of Prism type 1 L will be 1 inch for Prism type 2 L will be 0.75 inch and for Spheres type 1 & 2 the diameter (D) will 0.5” and 0.75” respectively.

With reference to the reading tables in Appendix A we define the measure of accuracy as:

$IL_{ABS} = |1.0 - L_{ABS}|$ inch

$IL_{PLA} = |\ 0.5 - L_{PLA}|$ inch

$IW_{ABS} = |0.5 - W_{ABS}|$ inch

$IW_{PLA} = |\ 0.5 - W_{PLA}|$ inch

$ID_{ABS} = |\ 0.5 - D_{ABS}|$ inch

$ID_{PLA} = |0.5 - D_{PLA}|$ inch

Ideally, the values for these *IL*, *IW* and *ID* should be zero. Their departure from zero, in either direction, is an inaccuracy in printing. In order to determine any significant difference in accuracy due to the two materials we used the student's t-tests.

We used the equal-variances test statistic based on the *F*-test to decide whether to perform the *t*-test of equality of two means with equal variance or unequal variance. The formula for the F test is F = $\frac{\sigma_1^2}{\sigma_2^2}$. The Hypothesis for the F-test are:-

$$H_0: \sigma_1^2 = \sigma_2^2$$

$$H_1: \sigma_1^2 \neq \sigma_2^2$$

For α = 0.05 with degree of freedom from the table of F-distribution F (9, 9) is 3.1789. If the variance is less than F table value then the hypothesis H_0 is established and t-test with equal variance was performed on the hypothesis. Otherwise in case H_0 being rejected the t-test with unequal variance was performed.

Two sample t-tests was conducted on the length and width of the rectangular prisms and on the diameter(s) of the sphere. In testing the null hypothesis that the specified dimensions (population mean) is equal to the determined means using the formula:

$$t = (x - \mu_{0)})/s\sqrt{n}$$

Two sample t-test was performed so as to get the desired p-value whether the means are different for the two materials i.e. PLA and ABS using the formula:

$$t = \overline{(X_1} - \overline{X}_2)/s_{X_1 X_2} \,.\sqrt{\frac{1}{n}}$$

To compare two material we used two sample t-test and the hypothesis of no difference:

$$H_0: \mu_1 = \mu_2$$

$$H_1: \mu_1 \neq \mu_2$$

Where H_0 states that the mean (mean of length/width/diameter) of both material are equal and H_1 hypothesis is the state of inequality. *p*-value were calculated from the t-test considering that if $p \leq 0.05$ we rejected the null hypothesis H_0 and establish the H_1 hypothesis.

Coefficient of Variation

The *coefficient of variation* is defined as the ratio of standard deviation and mean. It is measured in the percentage as the ratio is multiplied by 100. We calculated the coefficient of variance of the magnitude of inaccuracy in the length, width and diameter of between the ABS and PLA to observe the common trend in the variation. Lesser the variation more stable the material accuracy is reported. The formula for coefficient of variance is

$$\mathrm{CV} = \frac{\sigma}{\mu} * 100$$

Chapter IV: Results & Findings

Results

We measured the length and width of the printed rectangular prisms and the diameter of the spheres. Length and width of Rectangular prism type 1 were measured from the surface as depicted in Figure 6 and 7. For both the materials the measured values are tabulated in Table 5 and corresponding values of magnitude of inaccuracy are tabulated in table 6. The measured values for rectangular prism type 2 can be read in the Appendix A Table 13.

Table 5: Rectangular Prism type 1 Measured values

RECTANGULAR PRISM 1 [P1]				
Part No.	**ABS**		**PLA**	
	L	W	L	W
1	0.9853	0.5002	1.0203	0.5201
2	0.9883	0.5003	1.0021	0.5180
3	0.9856	0.5009	1.0193	0.5182
4	0.9853	0.5000	0.9855	0.5070
5	0.9842	0.5009	1.0228	0.5196
6	0.9825	0.5192	1.0204	0.5196
7	0.9855	0.5003	1.0192	0.5198
8	0.9859	0.5187	1.0152	0.5213
9	0.9852	0.5007	1.0193	0.5204
10	0.9856	0.5181	1.0225	0.5183

Table 6: Rectangular Prism type 1 measure of inaccuracy.

RECTANGULAR PRISM 1 [P1]				
Part No.	ABS		PLA	
	1-L	0.5 -W	1-L	0.5 -W
1	0.0147	0.0002	0.0203	0.0201
2	0.0117	0.0003	0.0021	0.018
3	0.0144	0.0009	0.0193	0.0182
4	0.0147	0	0.0145	0.007
5	0.0158	0.0009	0.0228	0.0196
6	0.0175	0.0192	0.0204	0.0196
7	0.0145	0.0003	0.0192	0.0198
8	0.0141	0.0187	0.0152	0.0213
9	0.0148	0.0007	0.0193	0.0204
10	0.0144	0.0181	0.0225	0.0183

Similarly we measured the diameter of sphere from three different points on the surface of the sphere as depicted in Figure 8. The measured diameters for Sphere type 1 are tabulated in Table 7 and corresponding values of magnitude of inaccuracy are tabulated in table 8. Similarly we measured the diameters of sphere type 2 which is tabulated in the Appendix A Table 17.

Table 7: Sphere type 1 measured diameters.

SPHERE 1						
Part No.	**ABS**			**PLA**		
	D_1	D_2	D_3	D_1	D_2	D_3
1	0.4784	0.4802	0.4825	0.5238	0.5247	0.5231
2	0.5193	0.4834	0.4972	0.5187	0.5236	0.4816
3	0.5000	0.5198	0.4996	0.4858	0.4785	0.4795
4	0.4854	0.4662	0.4995	0.4897	0.4845	0.4883
5	0.5004	0.4777	0.4847	0.5196	0.5204	0.5152
6	0.4786	0.4751	0.4987	0.5186	0.5147	0.4908
7	0.4884	0.4768	0.4769	0.5213	0.5166	0.5151
8	0.4818	0.4769	0.4756	0.5225	0.4872	0.4883
9	0.4812	0.4774	0.4936	0.5216	0.5186	0.5214
10	0.4841	0.4978	0.4993	0.5184	0.4875	0.4906

Table 8: Sphere type 1 measure of inaccuracy.

SPHERE 1						
Part No.	**ABS**			**PLA**		
	$0.5-D_1$	$0.5-D_2$	$0.5-D_3$	$0.5-D_1$	$0.5-D_2$	$0.5-D_3$
1	0.0216	0.0198	0.0175	0.0238	0.0247	0.0231
2	0.0193	0.0166	0.0028	0.0187	0.0236	0.0184
3	0	0.0198	0.0004	0.0142	0.0215	0.0205
4	0.0146	0.0338	0.0005	0.0103	0.0155	0.0117
5	0.0004	0.0223	0.0153	0.0196	0.0204	0.0152
6	0.0214	0.0249	0.0013	0.0186	0.0147	0.0092
7	0.0116	0.0232	0.0231	0.0213	0.0166	0.0151
8	0.0182	0.0231	0.0244	0.0225	0.0128	0.0117
9	0.0188	0.0226	0.0064	0.0216	0.0186	0.0214
10	0.0159	0.0022	0.0007	0.0184	0.0125	0.0094

Analysis

Analyzing the length of Prism 1

Conducting F-test on the length of rectangular prism tabulated in Appendix A Table 12.

F calculated value = 14.68

p -value = 0.0

F- Table value = 3.1789

If F_{cal} < F_{tab} H_0 is not rejected. In this case F_{cal} > F_{tab} the H_0 is rejected.

$$H_0: \sigma_1^2 = \sigma_2^2$$

$$H_1: \sigma_1^2 \neq \sigma_2^2$$

In case of *p -value,* if $p \leq 0.05$ the hypothesis H_0 is rejected.

H_0 is rejected in both cases and hence *t*-test with unequal variance will be performed.

Conducting two sample *t*-test on Rectangular prism tabulated in Appendix A Table 14 we get the following results

Mean of IL_{ABS} μ_1= 0.014660

Mean of IL_{PLA} μ_2 = 0.017560

p-Value = 0.171

$$H_0: \mu_1 = \mu_2$$

$$H_1: \mu_1 \neq \mu_2$$

If $p \leq 0.05$ we reject the null hypothesis H_0 and establish the H_1 hypothesis. In this case the p value is greater than 0.05. Hence establishing the null hypothesis H_0 and rejecting the H_1. By conventional criteria this difference is considered to be not statistically significant. Which shows that the material are performing in the same pattern.

Analyzing the width of Prism 1

We conduct the F-test on the variable of width W_{ABS} and W_{PLA} from the measured values of inaccuracy in Appendix A Table 12 we get the following results:

F calculated value = 4.529

p-value = 0.032

F- Table value = 3.1789

In this case $F_{cal} > F_{tab}$ and H_0 is rejected.

$$H_0: \sigma_1^2 = \sigma_2^2$$

$$H_1: \sigma_1^2 \neq \sigma_2^2$$

In case of P-value, if $P \leq 0.05$ again the hypothesis H_0 is rejected.

H_0 is rejected in both cases and hence *t*-test with unequal variance will be performed.

To compare two material we will use two sample t-test on the measure of inaccuracy. The hypothesis of difference will be

$$H_0: \mu_1 = \mu_2$$

$$H_1: \mu_1 \neq \mu_2$$

Conducting t-test we get the following results

Mean of IW_{ABS} μ_1= 0.005930

Mean of IW_{PLA} μ_2 = 0.018230

p-Value = 0.002

If $P \leq 0.05$ we reject the null hypothesis H_0 and establish the H_1 hypothesis. In this case $P < 0.05$. By conventional criteria this difference is considered to be statistically significant. The hypothesis H_0 of no difference is rejected establishing H_1, hence we can conclude that the materials differ significantly.

The difference of the mean with 95% Confidence Interval difference is (-0.01898, -0.00562) implies that

We are 95% confident that the true value of the parameter is in our confidence interval. Moreover the mean width of material ABS is less than the mean width of PLA, making ABS more accurate than the PLA.

Analyzing the length of Prism 2

Conducting F-test on Rectangular prism 2 tabulated in Appendix A Table 14 we get the following results

F calculated value = 1.866

p -value = 0.372

F- Table value = 3.1789

In this case $F_{cal} < F_{tab}$ the H_0 is not rejected,

$$H_0: \sigma_1^2 = \sigma_2^2$$

$$H_1: \sigma_1^2 \neq \sigma_2^2$$

In case of *p -value*, if $p \leq 0.05$ the hypothesis H_0 is rejected. In this case H_0 is not rejected.

H_0 is not rejected in both cases and hence t-test with equal variances will be performed.

Performing t-test on the length of rectangular Prism 2 with the hypotheses

$$H_0: \mu_1 = \mu_2$$

$$H_1: \mu_1 \neq \mu_2$$

Mean of IL_{ABS} $\mu_1 = 0.01776$

Mean of IL_{PLA} $\mu_2 = 0.01455$

p-Value = 0.386

If $p \leq 0.05$ we reject the null hypothesis H_0 and establish the H_1 hypothesis. In this case the *p* value is greater than 0.05. By conventional criteria this difference is considered to be not statistically significant.

Hence establishing the H_0 hypothesis and concluding that the materials have no difference in this case.

Analyzing the width of Prism 2

We conduct the F test and apply the same hypothesis on the variable of width W_{ABS} and W_{PLA} from the measured values of inaccuracy in Appendix A Table 14

F calculated value = 14

p-value = 0.001

F- Table value = 3.1789

In this case $F_{cal} > F_{tab}$ and H_0 is rejected.

$$H_0: \sigma_1^2 = \sigma_2^2$$

$$H_1: \sigma_1^2 \neq \sigma_2^2$$

In case of p-value, if $p \leq 0.05$ again the hypothesis H_0 is rejected.

H_0 is rejected in both cases and hence *t*-test with unequal variance will be performed.

Conducting t-test on Rectangular prism 2 tabulated in Appendix A Table 6 we get the following results

Mean of IW_{ABS} $\mu_1 = 0.00593$

Mean of IW_{PLA} $\mu_2 = 0.01823$

p- Value = 0.155

If $p \leq 0.05$ we reject the null hypothesis H_0 and establish the H_1 hypothesis. In this case the p value is greater than 0.05. By conventional criteria this difference is considered to be not statistically significant.

$$H_0: \mu_1 = \mu_2$$

$$H_1: \mu_1 \neq \mu_2$$

Hence establishing the H_0 hypothesis and concluding that the materials have no difference in this case.

Analyzing the diameter (D1) of Sphere 1

We conduct the F-test and apply the hypothesis on the variable of diameter D_{1ABS} and D_{1PLA} from the Table 16 in Appendix A.

F calculated value = 4

p-value = 0.056

F- Table value = 3.1789

In this case $F_{cal} > F_{tab}$ and H_0 is rejected.

$$H_0: \sigma_1^2 = \sigma_2^2$$

$$H_1: \sigma_1^2 \neq \sigma_2^2$$

In case of p-value, if $p \leq 0.05$ again the hypothesis H_0 is rejected.

H_0 is rejected in both cases and hence *t*-test with unequal variance will be performed.

To compare two materials we will use two sample t-test and the hypothesis of no difference will be

$$H_0: \mu_1 = \mu_2$$

$$H_1: \mu_1 \neq \mu_2$$

Where H_0 is the hypothesis that mean (μ) of ID_{ABS} is equal to the mean of ID_{PLA} and H_1 hypothesis states the means are not equal and there is a significant difference in terms of inaccuracy in length of rectangular prism.

After conducting t-test on we get the following results

Mean of ID_{1ABS} μ_1= 0.01418

Mean of ID_{1PLA} $\mu_2 = 0.01890$

p-value = 0.119

If $p \leq 0.05$ we reject the null hypothesis H_0 and establish the H_1 hypothesis. In this case the p value is greater than 0.05. By conventional criteria this difference is considered to be not statistically significant. Hence establishing the H_0 hypothesis and concluding that the materials have no difference in this case.

Analyzing the diameter (D2) of Sphere 1

We conduct the F-test and with the same hypothesis on the variable of width ID_{2ABS} and ID_{2PLA} from the Table 16 in Appendix A.

F calculated value = 3.315

p-value = 0.088

F- Table value = 3.1789

In this case $F_{cal} > F_{tab}$ and H_0 is rejected.

$$H_0: \sigma_1^2 = \sigma_2^2$$

$$H_1: \sigma_1^2 \neq \sigma_2^2$$

In case of p-value, if $p \leq 0.05$ again the hypothesis H_0 is rejected.

H_0 is rejected in both cases and hence *t*-test with unequal variance will be performed.

To compare two materials we will use two sample t-test and the hypothesis of no difference will be

$$H_0: \mu_1 = \mu_2$$

$$H_1: \mu_1 \neq \mu_2$$

where H_0 is the hypothesis that mean (μ) of ID_{ABS} is equal to the mean of ID_{PLA} and H_1 hypothesis states the means are not equal and there is a significant difference in terms of inaccuracy in length of rectangular prism.

After conducting t-test on we get the following results

Mean of ID_{2ABS} $\mu_1 = 0.02083$

Mean of ID_{2PLA} $\mu_2 = 0.01809$

p-value = 0.356

If $p \leq 0.05$ we reject the null hypothesis H_0 and establish the H_1 hypothesis. In this case the p value is greater than 0.05. By conventional criteria this difference is considered to be not statistically significant. Hence establishing the H_0 hypothesis and concluding that the materials have no difference in this case.

Analyzing the diameter (D3) of Sphere 1

We conduct the F-test with hypothesis on the variable of width ID_{3ABS} and ID_{3PLA}. The measured values of inaccuracy are tabulated in Table 16 Appendix A. We get the following results after applying the F-test

F calculated value = 3.692

p -value = 0.063

F- Table value = 3.1789

In this case $F_{cal} > F_{tab}$ and H_0 is rejected.

$$H_0: \sigma_1^2 = \sigma_2^2$$

$$H_1: \sigma_1^2 \neq \sigma_2^2$$

In case of p-value, if $p \leq 0.05$ again the hypothesis H_0 is rejected.

H_0 is rejected in both cases and hence *t*-test with unequal variance will be performed.

To compare two material we will use two sample t-test and the hypothesis of no difference will be

$$H_0: \mu_1 = \mu_2$$

$$H_1: \mu_1 \neq \mu_2$$

where H_0 is the hypothesis that mean (μ) of diameter D_{ABS} is equal to the mean of D_{PLA} and H_1 hypothesis states the means are not equal and there is a significant difference in terms of inaccuracy in length of rectangular prism.

Conducting t-test on we get the following results

Mean of ID_{3ABS} $\mu_1 = 0.00924$

Mean of ID_{3PLA} $\mu_2 = 0.01557$

p-value = 0.093

If $p \leq 0.05$ we reject the null hypothesis H_0 and establish the H_1 hypothesis. In this case the p value is greater than 0.05. By conventional criteria this difference is considered to be not statistically significant. Hence establishing the H_0 hypothesis and concluding that the materials have no difference in this case.

Analyzing the diameter (D1) of Sphere 2

We conduct the F-test with the hypothesis on the variable of width ID_{1ABS} and ID_{1PLA}. The measured values of inaccuracy are tabulated in Table 18 Appendix A.

F calculated value = 1.508

P-value = 0.553

F- Table value = 3.1789

In this case $F_{cal} < F_{tab}$ and H_0 is not rejected.

$$H_0: \sigma_1^2 = \sigma_2^2$$

$$H_1: \sigma_1^2 \neq \sigma_2^2$$

In case of *p -value*, if $p \leq 0.05$ the hypothesis H_0 is rejected but in this case H_0 is not rejected.

H_0 is not rejected in both cases and hence t-test with equal variance will be performed in this case.

To compare two material we will use two sample t-test and the hypothesis of no difference will be

$$H_0: \mu_1 = \mu_2$$

$$H_1: \mu_1 \neq \mu_2$$

where H_0 is the hypothesis that mean (μ) of ID_{1ABS} is equal to the mean of ID_{1PLA} and H_1 hypothesis states the means are not equal and there is a significant difference in terms of inaccuracy in length of rectangular prism.

Conducting t-test we get the following results

Mean of ID_{1ABS} $\mu_1 = 0.01735$

Mean of ID_{1PLA} $\mu_2 = 0.01241$

p- Value = 0.208

If $p \leq 0.05$ we reject the null hypothesis H_0 and establish the H_1 hypothesis. In this case the p value is greater than 0.05. By conventional criteria this difference is considered to be not statistically significant. Hence establishing the H_0 hypothesis and concluding that the materials have no difference in this case.

Analyzing the diameter (D2) of Sphere 2

We conduct the F- test and apply with same hypothesis on the variable of width ID_{2ABS} and ID_{2PLA} from the Table 18 in Appendix A.

F calculated value = 6.533

p-value = 0.01

F- Table value = 3.1789

In this case $F_{cal} > F_{tab}$ and H_0 is rejected.

$$H_0: \sigma_1^2 = \sigma_2^2$$

$$H_1: \sigma_1^2 \neq \sigma_2^2$$

In case of *p -value*, if $p \leq 0.05$ again the hypothesis H_0 is rejected.

H_0 is rejected in both cases and hence t-test with unequal variance will be performed in this case.

To compare two material we will use two sample t-test and the hypothesis of no difference will be

$$H_0: \mu_1 = \mu_2$$

$$H_1: \mu_1 \neq \mu_2$$

where H_0 is the hypothesis that mean (μ) of ID_{ABS} is equal to the mean of ID_{PLA} and H_1 hypothesis states the means are not equal and there is a significant difference in terms of inaccuracy in length of rectangular prism.

After conducting t-test on we get the following results

Mean of ID_{2ABS} μ_1= 0.02144

Mean of ID_{2PLA} μ_2 = 0.001859

P-Value = 0.407

If $p \leq 0.05$ we reject the null hypothesis H_0 and establish the H_1 hypothesis. In this case the p value is greater than 0.05. By conventional criteria this difference is considered to be not statistically significant. Hence establishing the H_0 hypothesis and concluding that the materials have no difference in this case.

Analyzing the diameter (D3) of Sphere 2

We conduct the F-tests the on the variable of width ID_{3ABS} and ID_{3PLA}. The measured values of inaccuracy are tabulated in Table 18 Appendix A.

F calculated value = 1

p -value = 0.989

F- Table value = 3.1789

In this case $F_{cal} < F_{tab}$ and H_0 is not rejected.

$$H_0: \sigma_1^2 = \sigma_2^2$$

$$H_1: \sigma_1^2 \neq \sigma_2^2$$

In case of P-value, if $P \leq 0.05$ again the hypothesis H_0 is not rejected.

H_0 is not rejected in both cases and hence t-test with equal variances will be performed in this case.

To compare two material we will use two sample t-test and the hypothesis of will be

$$H_0: \mu_1 = \mu_2$$

$$H_1: \mu_1 < \mu_2$$

Conducting t-test on the diameter of Sphere 2 D3 we get the following results

Mean of ID_{3ABS} μ_1= 0.02193

Mean of ID_{3PLA} μ_2 = 0.01229

p -value = 0.002

If $p \leq 0.05$ we reject the null hypothesis H_0 and establish the H_1 hypothesis. In this case the p value is less than 0.05. By conventional criteria this difference is considered to be statistically significant. Hence rejecting the H_0 hypothesis and concluding that the materials have difference in this case.

$$H_0: \mu_1 = \mu_2$$

$$H_1: \mu_1 < \mu_2$$

We can observe from the given values:

$$ID_{3ABS}\ \mu_1 > ID_{3PLA}\ \mu_2$$

From the hypothesis H_1 we can conclude that PLA is more accurate than ABS in this case.

Findings

From the analysis we observed that in eight cases there is no significant difference in the print accuracy of the material. There is significant difference in two cases, from the result of t-test to establish the superiority of a material over each other we observed that ABS is more accurate in one case and PLA is more accurate in the other. The results of the analysis is tabulated in the table 9.

Table 9: Summary if the results.

S No.	Part type		Difference in material
1	Prism Type 1 Length	(P1L)	No significant Difference
2	Prism Type 1 Width	(P1W)	ABS is more accurate
3	Prism Type 2 Length	(P2L)	No significant Difference
4	Prism Type 2 Width	(P2W)	No significant Difference
5	Sphere Type 1 Diameter 1	(S1D1)	No significant Difference
6	Sphere Type 1 Diameter 2	(S1D2)	No significant Difference
7	Sphere Type 1 Diameter 3	(S1D3)	No significant Difference
8	Sphere Type 2 Diameter 1	(S2D1)	No significant Difference
9	Sphere Type 2 Diameter 2	(S2D2)	No significant Difference
10	Sphere Type 2 Diameter 3	(S2D3)	PLA is more accurate

Coefficient of Variation

We calculated the coefficient of variation of the magnitude of inaccuracy in the length, width and diameter of between the ABS and PLA to observe the common trend in the variation. Lesser the variation more stable the material accuracy is reported. The formula for coefficient of variance is:

$$CV = \frac{\sigma}{\mu} * 100$$

Table 10: Coefficient of Variation showing the stability of the materials.

Part	ABS		PLA		CV OF ABS	CV OF PLA	STABILITY
	SD	Mean	SD	MEAN			
P1L	0.001439	0.1466	0.006056	0.1756	0.981582538	3.448747153	ABS
P1W	0.008798	0.00593	0.004083	0.01823	148.3642496	22.39714756	PLA
P2L	0.009177	0.01776	0.006743	0.01455	51.6722973	46.34364261	PLA
P2W	0.001846	0.01177	0.006451	0.01503	15.68394223	42.92082502	ABS
S1D1	0.13055	0.48976	0.01398	0.514	26.6559131	2.719844358	PLA
S1D2	0.015132	0.48313	0.018638	0.50563	3.132076253	3.686094575	ABS
S1D3	0.009815	0.49076	0.017167	0.49939	1.999959247	3.437593865	ABS
S2D1	0.009273	0.01735	0.007561	0.01241	53.44668588	60.92667204	ABS
S2D2	0.009883	0.02144	0.003875	0.01859	46.09608209	20.84454008	PLA
S2D3	0.005904	0.02193	0.005933	0.1229	26.92202462	4.827502034	PLA

From the Table 10 we can compare the stability of materials on the basis of coefficient of variation. We observe that in five cases the ABS is more stable and PLA is similarly stable in five cases. In this analysis of coefficient of variation we conclude that both material does not depict any variation from each other and are behaving in the same manner in terms of stability in inaccuracy.

Chapter V: Summary and Discussion

In this research we presented an approach on testing the accuracy of the two printing materials ABS and PLA. We printed ten rectangular prism and spheres of each material in two different set of measurements. The length and width and diameter of the printed rectangular prisms parts and sphere was then measured with micrometer respectively. The readings of the both materials were tabulated and compared against each other to measure the inaccuracy in the length and width of the measured values. The comparison was carried out calculating the standard deviation and the mean of the inaccuracy of each compared length and width with respect to the material. Corresponding F-test and t-test was performed to analyze the data measured.

Based on statistical analysis of the inaccuracies of length, width and diameter of the parts we concluded that both the material in our experiment are behaving in the same manner. There is no significant difference in accuracy between ABS and PLA. Accuracy also varies with machine and the manufacturers. The Flashforge creator pro 3D printer is an average prototype machine. We anticipate better results if the research is conducted on an industrial grade prototype machine.

The coefficient of variance tabled in table 10 shows that the accuracy or stability of the materials is uniform. The number of cases which shows ABS is more accurate is equivalent to the number of cases where PLA is stable. It shows that there is no significant difference in the accuracy of the two materials. Moreover if there is any significant difference found, it is in a uniform pattern.

PLA as mentioned earlier is plant based and uses less temperature for extrusion, it flows more smoothly than ABS this is the reason it gives better results in printing sharp corners, stronger binding between layers. The glow texture and other properties varies from vendors to vendors. The strength, flexibility, machinability, and higher temperature resistance make ABS often a preferred plastic by mechanical engineers. The difference of the print temperatures plays an important role that affects the accuracy, strength and resilience of the material. In other words PLA is good for hobbyist printing needs while ABS is better option for industrial requirements.

It was observed that ABS parts printed in white color appeared to have greater roughness than the parts printed in blue color. In a future study the effect of color on texture can be investigated. It all comes down to what is the requirement of the printed part. For example if a user wants to print machine parts one will go for ABS as it has longer lifespan and more sturdy in nature but if a user wants to print utensil to use it for storing food one will go for PLA as it is plant based and bio-degradable. The finish and glow is more in PLA and it takes less time as compared to ABS. There are many factors that affect the printing time such as the temperature of the extruder and the temperature of the printbed. PLA requires less temperature as compared to ABS in both extrusion and printbed. It can be printed on cold surface. While printing in PLA the ventilation of the printbed is required as it smells differently and it is recommended to allow more air to flow for printing. ABS does not have any air flow restrictions.

Future Work

The work described in this project has been concerned to establish the superiority of 3D printing materials over one another. Although the results presented here have demonstrated the difference on accuracy between the two 3D printing materials ABS and PLA, it could be developed in a number of ways by overcoming the limitations we had in this research such as number of parts printed was 40 for each case. The larger sample data with more degree of freedom will give us reliable results. The plastic filaments can be compared with other material like wood and steel to establish the comparable study which can be used at industrial level. The further research on industrial grade machine would give better results.

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APPENDIX A: LIST OF TABLES

Table 11: Rectangular Prism Measured values

RECTANGULAR PRISM 1 [P1]				
Part No.	ABS		PLA	
	L	W	L	W
1	0.9853	0.5002	1.0203	0.5201
2	0.9883	0.5003	1.0021	0.5180
3	0.9856	0.5009	1.0193	0.5182
4	0.9853	0.5000	0.9855	0.5070
5	0.9842	0.5009	1.0228	0.5196
6	0.9825	0.5192	1.0204	0.5196
7	0.9855	0.5003	1.0192	0.5198
8	0.9859	0.5187	1.0152	0.5213
9	0.9852	0.5007	1.0193	0.5204
10	0.9856	0.5181	1.0225	0.5183

Table 12: Rectangular Prism Measure of Inaccuracy.

RECTANGULAR PRISM 1 [P1] |LW|				
Part No.	ABS		PLA	
	1-L	0.5 -W	1-L	0.5 -W
1	0.0147	0.0002	0.0203	0.0201
2	0.0117	0.0003	0.0021	0.018
3	0.0144	0.0009	0.0193	0.0182
4	0.0147	0	0.0145	0.007
5	0.0158	0.0009	0.0228	0.0196
6	0.0175	0.0192	0.0204	0.0196
7	0.0145	0.0003	0.0192	0.0198
8	0.0141	0.0187	0.0152	0.0213
9	0.0148	0.0007	0.0193	0.0204
10	0.0144	0.0181	0.0225	0.0183

Table 13: Rectangular Prism 2 measured values

RECTANGULAR PRISM 2 [P2]				
Part No.	ABS		PLA	
	L	W	L	W
1	0.7485	0.7379	0.7377	0.7693
2	0.7686	0.7399	0.7724	0.7394
3	0.7681	0.7406	0.7369	0.7696
4	0.7725	0.7373	0.7716	0.7397
5	0.7738	0.7368	0.7698	0.7625
6	0.7742	0.7403	0.7705	0.7358
7	0.7501	0.7392	0.7383	0.7714
8	0.7730	0.7387	0.7377	0.7708
9	0.7726	0.7368	0.7502	0.7514
10	0.7732	0.7348	0.7384	0.7702

Table 14: Rectangular Prism 2 Measure of Inaccuracy.

RECTANGULAR PRISM 2 [P2]				
Part No.	ABS		PLA	
	0.75-L	0.75 -W	0.75-L	0.75 -W
1	0.0015	0.0121	0.0123	0.0193
2	0.0186	0.0101	0.0224	0.0106
3	0.0181	0.0094	0.0131	0.0196
4	0.0225	0.0127	0.0216	0.0103
5	0.0238	0.0132	0.0198	0.0125
6	0.0242	0.0097	0.0205	0.0142
7	0.0001	0.0108	0.0117	0.0214
8	0.023	0.0113	0.0123	0.0208
9	0.0226	0.0132	0.0002	0.0014
10	0.0232	0.0152	0.0116	0.0202

Table 15: Sphere 1 measured values.

SPHERE 1						
Part No.	**ABS**			**PLA**		
	D_1	D_2	D_3	D_1	D_2	D_3
1	0.4784	0.4802	0.4825	0.5238	0.5247	0.5231
2	0.5193	0.4834	0.4972	0.5187	0.5236	0.4816
3	0.5000	0.5198	0.4996	0.4858	0.4785	0.4795
4	0.4854	0.4662	0.4995	0.4897	0.4845	0.4883
5	0.5004	0.4777	0.4847	0.5196	0.5204	0.5152
6	0.4786	0.4751	0.4987	0.5186	0.5147	0.4908
7	0.4884	0.4768	0.4769	0.5213	0.5166	0.5151
8	0.4818	0.4769	0.4756	0.5225	0.4872	0.4883
9	0.4812	0.4774	0.4936	0.5216	0.5186	0.5214
10	0.4841	0.4978	0.4993	0.5184	0.4875	0.4906

Table 16: Sphere 1 measure of inaccuracy.

SPHERE 1						
Part No.	**ABS**			**PLA**		
	$0.5-D_1$	$0.5-D_2$	$0.5-D_3$	$0.5-D_1$	$0.5-D_2$	$0.5-D_3$
1	0.0216	0.0198	0.0175	0.0238	0.0247	0.0231
2	0.0193	0.0166	0.0028	0.0187	0.0236	0.0184
3	0	0.0198	0.0004	0.0142	0.0215	0.0205
4	0.0146	0.0338	0.0005	0.0103	0.0155	0.0117
5	0.0004	0.0223	0.0153	0.0196	0.0204	0.0152
6	0.0214	0.0249	0.0013	0.0186	0.0147	0.0092
7	0.0116	0.0232	0.0231	0.0213	0.0166	0.0151
8	0.0182	0.0231	0.0244	0.0225	0.0128	0.0117
9	0.0188	0.0226	0.0064	0.0216	0.0186	0.0214
10	0.0159	0.0022	0.0007	0.0184	0.0125	0.0094

Table 17: Sphere 2 measured diameters.

SPHERE 2						
Part No.	ABS			PLA		
	D_1	D_2	D_3	D_1	D_2	D_3
1	0.7145	0.7145	0.7177	0.7304	0.7253	0.7332
2	0.7216	0.7260	0.7259	0.7334	0.7308	0.7417
3	0.7484	0.7318	0.7216	0.7696	0.7369	0.7417
4	0.7381	0.7278	0.7284	0.7384	0.7303	0.7723
5	0.7292	0.7293	0.7312	0.7691	0.7336	0.7702
6	0.7337	0.7371	0.7270	0.7454	0.7305	0.7402
7	0.7335	0.7284	0.7332	0.7500	0.7358	0.7341
8	0.7354	0.7129	0.7322	0.7699	0.7254	0.7435
9	0.7358	0.7308	0.7380	0.7455	0.7336	0.7434
10	0.7363	0.7470	0.7255	0.7414	0.7319	0.7418

Table 18: Sphere 2 measure of inaccuracy.

SPHERE 2						
Part No.	ABS			PLA		
	$0.75-D_1$	$0.75-D_2$	$0.75-D_3$	$0.75-D_1$	$0.75-D_2$	$0.75-D_3$
1	0.0355	0.0355	0.0323	0.0196	0.0247	0.0168
2	0.0284	0.024	0.0241	0.0166	0.0192	0.0083
3	0.0016	0.0182	0.0284	0.0196	0.0131	0.0083
4	0.0119	0.0222	0.0216	0.0116	0.0197	0.0223
5	0.0208	0.0207	0.0188	0.0191	0.0164	0.0202
6	0.0163	0.0129	0.023	0.0046	0.0195	0.0098
7	0.0165	0.0216	0.0168	0	0.0142	0.0159
8	0.0146	0.0371	0.0178	0.0199	0.0246	0.0065
9	0.0142	0.0192	0.012	0.0045	0.0164	0.0066
10	0.0137	0.003	0.0245	0.0086	0.0181	0.0082